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13. SUPPLEMENTARY NOTES

14. ABSTRACT

1. Development of a criterion for estimator algorithm selection [229].
2. Comparison of the track-to-track association with centralized tracking [237, 280, 281].
3. Development of a practical algorithm for handling OOSMs [243, 274, 275].
4. Development of a systematic decision for estimating the number of targets in a surveillance system [248, 285].
5. Association of broken track segments [259].
6. Use of Joint Multiple Bin Processing Detection for Localization of Multiple Targets [261].
7. Development of a special Signal Processing technique for multipath environment [262, 268].
8. Comparison of various tracklet methods [263].

15. SUBJECT TERMS

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FINAL REPORT
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ESTIMATION WITH MULTISENSOR FUSION

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1 Objectives

Our work dealt with the development of practical advanced algorithms for optimal processing of the information obtained from various remote sensing devices (radar, ESM or electro-optical) for surveillance and tracking targets. The processing consists of integration/filtering of the sensor data across time and fusion across sensors with the main goal being overcoming the inherent limitations of real-world sensors (accuracy and reliability) due to noise — which cause false alarms — and other factors, such as low observable (LO) targets — which lead to low detection probability.

The following were the specific objectives of the research, with the corresponding publication numbers in brackets:

1. Development of a criterion for estimator algorithm selection [229].
2. Comparison of the track-to-track association with centralized tracking [237, 280, 281].
3. Development of a practical algorithm for handling OOSMs [243, 274, 275].
4. Development of a systematic decision for estimating the number of targets in a surveillance system [248, 285].
5. Association of broken track segments [259].
6. Use of Joint Multiple Bin Processing Detection for Localization of Multiple Targets [261].
7. Development of a special Signal Processing technique for multipath environment [262, 268].
8. Comparison of various tracklet methods [263].
9. Investigation of the correlation between radar angle measurements [264].
10. Multiple sensor bias estimation [265, 269, 279].
11. Investigation of the target to sensor intervisibility [266].
12. Incorporation of target class information into tracking [267].
13. Survey of PDA applications for tracking in clutter [270].
14. Data association using fast methods [271].
15. Missile trajectory estimation/identification using passive sensors [272].
16. Optimal UAV placement for surveillance [273, 284].
17. Evaluation of IR pixel size on tracking [276].
18. Augmentation of the Probability Hypothesis Density method with data association [277].
19. Investigation of the Kalman-Levy filter for tracking [278].
20. Bias Estimation for General Asynchronous Sensors [282].
21. Survey of Probabilistic Data Association Techniques for Target Tracking in Clutter [283].
22. General Track-to-Track Association for Tracks with Dependent Errors [286].
23. The connection between the IMM Estimator and Optimal Estimator for Hybrid Systems [288].
24. Development of a measurement extractor for Unresolved Targets observed with a Monopulse Radar [289].
25. Derivation of The Dimensionless Score Function for Measurement to Track Association [290].

26. Incorporation of Features and Attributes into Track-to-Track Association [291].

27. New Signal Processing method for Detection and Localization of Multiple Unresolved Extended Objects with a Monopulse Radar [292].

28. Tracking of Closely Spaced Objects Using Monopulse Measurements [293].

29. Performance evaluation of Multisensor Target Tracking with Bias Compensation [294].

30. Discrimination between YATO and YANTO when attacked by a SAM [295].

31. Multi-Platform Cooperation for Covert Tracking [296], [297].

32. Development of a Hierarchical Benchmark Association Problem in Missile Defense [299].

33. Combination of Track Labeling with the Probability Hypothesis Density Filter for Multitarget-Multisensor Tracking [300].

34. An equation-challenged review of Probabilistic Data Association Techniques for Target Tracking with Applications to Sonar, Radar and EO Sensors [301].

2 Status of Effort

1. We developed a criterion for estimator algorithm selection based on the maneuvering index [229].
2. Track-to-track association was compared to centralized tracking in realistic AFRL supplied scenarios [237, 280, 281].
3. A practical algorithm for handling multi-step lag OOSMs was developed [243, 274, 275].
4. The Minimum Description Length criterion was adapted to provide a systematic decision for estimating the number of targets in a surveillance system [248, 285].
5. The methodology for using an assignment algorithm for association of broken track segments was developed [259].
6. An ML algorithm was developed for Multiple Bin Processing Detection and Localization of multiple unresolved targets [261].
7. A measurement extractor was developed for a multipath environment [262, 268].
8. The comparison of various tracklet methods was carried out [263].
9. The correlation between radar angle measurements was evaluated [264].
10. Algorithms for the synchronous as well asynchronous case were developed for multiple sensor bias estimation [265, 269, 279].
11. The target to sensor intervisibility was quantified [266].
12. The modified cost function that incorporates target class information into tracking was developed and used [267].
13. A comprehensive survey of PDA applications for tracking in clutter was carried out [270].
14. Data association using linear programming was initiated [271].
15. An algorithm for missile trajectory estimation/identification using passive sensors was developed [272].
16. An algorithm for optimal UAV placement for surveillance was obtained [273, 284].
17. The tracking performance was related to the IR pixel size [276].
18. The Probability Hypothesis Density method was combined with data association [277].
19. The use of the Kalman-Levy filter for tracking was investigated [278].
20. An exact Bias Estimation algorithm for General Asynchronous Sensors (radars) was derived [282].
21. An extensive survey of Probabilistic Data Association Techniques for Target Tracking in Clutter was presented [283].
22. The exact ML Track-to-Track Association for Tracks with Dependent Errors from an arbitrary number of sensors was developed [286].
23. It was shown that IMM Estimator carries out the "mixing" just like the Optimal Estimator for Hybrid Systems [288].
24. It was shown that one can extract separate measurements for two "Unresolved" Targets in the same range bin and beam from a Monopulse Radar [289].
25. The correct dimensionless Score Function for Measurement to Track Association was derived [290].

26. Continuous Features and discrete Attributes were incorporated simultaneously into Track-to-Track Association [291].

27. A new Signal Processing method for Detection and Localization of Multiple Unresolved Extended Objects with a Monopulse Radar was developed [292].

28. Several algorithms for Tracking of Closely Spaced Objects Using Monopulse Measurements were compared and new estimation based on the I and Q radar channel data was developed [293].

29. We quantified the Performance of Multisensor Target Tracking with our recently developed Bias Compensation [294].

30. We developed a Discrimination algorithm to decide whether an aircraft is the target of a MANPAD when one has been fired [295].

31. We developed a fusion algorithm between an active and a passive sensor on different platforms for Covert Tracking [296], [297].

32. We developed a BLEA-inspired Hierarchical Benchmark Association Problem in Missile Defense [299].

33. Combined Track Labeling with the Probability Hypothesis Density Filter for Multitarget-Multisensor Tracking [300].

34. We wrote up a tutorial (equation-challenged) review of Probabilistic Data Association Techniques for Target Tracking with Applications to Sonar, Radar and EO Sensors [301].

3 Accomplishments and New Findings

1. The criterion for estimator algorithm selection based on the maneuvering index allows judicious selection between a KF and an IMM estimator for applications [229].

2. Track-to-track association is only slightly inferior to centralized tracking in realistic AFRL supplied scenarios [237, 280, 281].

3. A multi-step lag OOSM can be used to update the current state in a single step [243, 274, 275].

4. The Minimum Description Length criterion is an efficient way for estimating the number of targets in a surveillance system [248, 285].

5. The association of broken track segments significantly increases the track continuity [259].

6. Multiple Bin Processing allows detection and localization of multiple unresolved targets [261].

7. The measurement extractor developed for a multipath environment is the key in solving the latest benchmark tracking problem [262, 268].

8. The various tracklet methods are significantly inferior to full rate tracking [263].

9. The use of the correlation between radar angle measurements can improve tracking performance [264].

10. The algorithms developed for the synchronous as well asynchronous case are statistically efficient for multiple sensor bias estimation [265, 269, 279].

11. The target to sensor intervisibility can be evaluated for either covert missions or surveillance [266].

12. The modified cost function that incorporates target class information into tracking yields significant performance enhancements [267].

13. The survey of PDA applications for tracking in clutter showed the ability to track LOs [270].

14. Data association using linear programming is faster than Lagrangian relaxation [271].

15. An algorithm for missile trajectory estimation/identification using passive sensors can be used to identify the aim of the missile [272].

16. The algorithm for optimal UAV placement for surveillance can improve their utilization [273, 284].

17. The tracking performance can be optimized w.r.t. IR pixel size [276].

18. The Probability Hypothesis Density method combined with data association is the key to a seemless group-individual tracking scheme [277].

19. The use of the Kalman-Levy filter for tracking yields marginal benefits [278].

20. The exact Bias Estimation algorithm for General Asynchronous Sensors (radars) meets the CRLB [282].

21. An extensive survey of Probabilistic Data Association Techniques for Target Tracking in Clutter was published in the premier journal of IEEE [283].

22. The general Track-to-Track Association for Tracks with Dependent Errors from an arbitrary number of sensors allows practical MSI [286].

23. The success of the IMM Estimator is due to the fact that it carries out the "mixing" just like the Optimal Estimator for Hybrid Systems [288].

24. One can extract separate measurements for two "Unresolved" Targets in the same range bin and beam from a Monopulse Radar [289].

25. The correct dimensionless Score Function for Measurement to Track Association requires the spatial density of "extraneous targets" [290].

26. Continuous Features and discrete Attributes were incorporated into Track-to-Track Association allow "attribute gating" [291].

27. Detection and Localization of Multiple Unresolved Extended Objects with a Monopulse Radar is possible using matched filter samples from adjacent bins [292].

28. The new estimation based on the I and Q radar channels allows the tracker to operate directly on the internal radar data [293].

29. The Performance of Multisensor Target Tracking with our recently developed Bias Compensation is near the performance with perfect bias compensation [294].

30. The Discrimination algorithm to decide whether an aircraft is the target of a MANPAD when one has been fired allows to distinguish between YATO and YANTO as long as their separation is 200m [295].

31. The fusion algorithm between an active and a passive sensor on different platforms allows LPI Tracking [296], [297].

32. The Hierarchical Benchmark Association Problem in Missile Defense shows the superiority of the S-D assignment over the sequential 2-D [299].

33. Track Labeling enhances significantly the performance of the Probability Hypothesis Density Filter for Multitarget-Multisensor Tracking [300].

34. The equation-challenged tutorial on the Probabilistic Data Association Techniques for Target Tracking with Applications to Sonar, Radar and EO Sensors made it accessible for a wide audience, including even managers [301].

4 Personnel Supported

Faculty: Yaakov Bar-Shalom, K.R. Pattipati, P.K. Willett and T. Kirubarajan.
Graduate Students: L. Lin (graduated), X. Lin (graduated), S. Yeom, X. Zhang (graduated), J. Areta.

5 Publications

Published and/or accepted for publication during the report period
30 journal papers, 27 conference papers

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243.(J120) Y. Bar-Shalom, H. Chen and M. Mallick,"One-Step Solution for the General Out-of-Sequence Measurement Problem in Tracking", **IEEE Trans. Aerosp. Electronic Systems**, AES-40(1):27–37, Jan. 2004.

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248.(J123) H. Chen, T. Kirubarajan, Y. Bar-Shalom and K. R. Pattipati, "MDL Approach for Multiple Low-Observable Track Initiation", **IEEE Trans. Aerosp. Electronic Systems**, AES-39(3):862–882, July 2003.

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255.(J125) M. L. Hernandez, T. Kirubarajan and Y. Bar-Shalom, "Multisensor Resource Deployment in the Presence of Clutter Using Cramer-Rao Lower Bounds", **IEEE Trans. Aerosp. Electronic Systems**, AES-40(2):399–416, April 2004.

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261.(J128) X. Zhang, P.K. Willett and Y. Bar-Shalom, "Monopulse Radar Detection and Localization of Multiple Targets via Joint Multiple Bin Processing", **IEEE Trans. on Signal Processing**, 53(4):1225–1236, April 2005. Also in **Proc. 2003 IEEE Radar Conf.**, Huntsville, AL, May 2003.

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264.(J130) P. K. Willett, W. D. Blair and Y. Bar-Shalom, "On the Correlation Between Horizontal and Vertical Monopulse Measurements", **IEEE Trans. Aerosp. Electronic Systems**, AES-39(2):533–549, April 2003.

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273. A. Sinha, T. Kirubarajan and Y. Bar-Shalom, "Optimal Cooperative Placement of GMTI UAVs for Ground Target Tracking", **Proc. 2004 IEEE Aerospace Conf.**, Big Sky, MT, March 2004.

274. P. G. Lanzkron and Y. Bar-Shalom, "A Two-Step Method for Out-of-Sequence Measurements", **Proc. 2004 IEEE Aerospace Conf.**, Big Sky, MT, March 2004.

275.(J137) Y. Bar-Shalom and H. Chen, "IMM Estimator with Out-of-Sequence Measurements", **IEEE Trans. Aerosp. Electronic Systems**, AES-41(1):90– 98, Jan. 2005.

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in **Proc. SPIE Conf. Signal and Data Processing of Small Targets**, #5913-50, San Diego, CA, Aug. 2005.

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310. Ozgur Erdinc, P. Willett and Y. Bar-Shalom, "The Probability Hypothesis Density Filter in Detection Target Spawn", **Proc. SPIE Conf. Signal and Data Processing of Small Targets**, #6236-43, Orlando, FL, April 2006.

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312. Huimin Chen and Y. Bar-Shalom, "Track Fusion with Legacy Track Sources", **Proc. 9th Intn'l Conf. on Information Fusion**, Florence, Italy, July 2006.

Ph.D. dissertations

20. X. D. Lin, "Multisensor-Multitarget Bias Estimation for Asynchronous Sensors", April 2004. Research Engineer at SIRF.

21. L. Lin, "Data Association Combined with the Probability Hypothesis Density Function Filter for Multitarget Tracking", April 2004. Research Engineer at UTRC.

22. X. Zhang, "Information Limits in Remote Sensing and Target Tracking", May 2005. Currently Postdoctoral fellow at Princeton Univ.

6 Interactions/Transitions

National courses were given at IEEE Radar Conf. in April 2004, IEEE Systems Symposium, March 2004, JSSEO [Joint SIAP (Single Integrated Air Picture) System Engineering Office], Arlington, VA, March 2005, Lockheed Martin, Moorestown, NJ, July 2005 and FUSION 2005, Philadelphia, PA.

International courses were given at the Radar India Symposium, Dec. 2003 and FUSION 2006, Florence, Italy.

The PI gave his IEEE AESS Distinguished Lecture at the FUSION'03 Conf. in June 2003 and IEEE Toronto Section, Nov. 2005.

Keynote addresses were given at the Radar India Symposium, Dec. 2003, and IEEE Systems Symposium, March 2004.

AFRL (WPAFB; Erik Blasch) is using the OOSM algorithm for AF applications.

Northrop-Grumman (Baltimore, MD) will use our missile aim identification algorithm for the JSF MWS.

Northrop-Grumman (Bethpage, NY) is using one of our assignment algorithms for passive target localization from ESM (Electronic Support Measures) sensors.

The next generation air-to-ground surveillance systems from UAV (unmanned aerial vehicles), under development by DARPA, will use the VS-IMM (variable structure IMM) tracker developed in a recent Ph.D. dissertation at UConn.

Our image feature (target centroid) extraction and tracking algorithm has been implemented in the ARROW ABM (Antiballistic Missile) sponsored by BMDO (Ballistic Missile Defense Organization, now MDA). This system has reached operational capability.

ETC (Mystic, CT) implemented our algorithm for tracking a low SNR (Signal to Noise Ratio) maneuvering target with an active sonar. This has been transitioned to the USN Fleet.

Raytheon (Bedford, MA) has implemented a JPDA (Joint Probabilistic Data Association) tracker for their ASDE-X (Airport Surface Detection Equipment), ROTHR (Relocatable Over the Horizon Radar), GBR-P (Ground Based Radar Prototype for National Missile Defense) and in the THAAD (Theater High Altitude Antiballistic Defense).

The new Air Traffic Control tracking algorithm Raytheon developed for the FAA (as well as export) is based on the IMM estimator.

The French Navy is using the LO (Low Observable — low SNR) passive track detector named "The Magician", based on our ML-PDA algorithm, from extremely weak target signals.

BAE Systems (Nashua, NH) is using our ML-PDA algorithm for passive tracking for the Electronic Warfare system of the JSF (F-35).

ORINCON (San Diego, CA) adopted the VS-IMM for the next generation GMTI tracker.

Alphatech (Burlington, MA) adopted our tracker with out-of-sequence measurements for the GMTI tracker and will use our bias estimation algorithm.

QinetiQ (formerly DERA, UK) developed an optimal passive sensor deployment policy for low SNR target tracking based on joint work with us, relying on our "information reduction factor" for a cluttered environment; They also used our unbiased conversion of radar measurements from sensor coordinates to Cartesian for enhanced accuracy tracking.

NUMERICA (Ft. Collins, CO; Aubrey Poore) is using the multisensor maximum-depth association algorithm in their Hercules Project work for MDA. Impact: This increases significantly the time depth of an assignment algorithm, which, in the presence of data from multiple sensors would be reduced by a factor equal to the number of sensors.

7 New discoveries, inventions or patent disclosures

None

8 Honors/Awards

Yaakov Bar-Shalom:

- Fellow of IEEE
- Distinguished Lecturer of IEEE AES Society
- Member of the Connecticut Academy of Science and Engineering (2002)
- Appointed as Board of Trustees Distinguished Professor at UConn (2002).
- Marianne E. Klewin Professor in Engineering since 2004
- President of International Society of Information Fusion (ISIF) for 2000 and 2002. Vice President for Publications for 2003–06.

K.R. Pattipati:

- Fellow of IEEE
- Editor-in-Chief of IEEE Trans. on SMC

P.K. Willett:

- Fellow of IEEE
- Editor-in-Chief of IEEE Trans. on AES